A REVIEW OF THE NASA/OAST CRYOGENIC COOLERS TECHNOLOGY PROGRAM

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SUMMARY

An ongoing NASA research and technology program provides for the development of low and ultra-low temperature cryogenic cooler systems for future space missions. These include mechanical, solid cryogen, gas adsorption, superfluid helium, helium-3, and magnetic (adiabatic demagnetization) coolers.

Operating lifetimes required vary from a few weeks for a Shuttle/Spacelab mission to as long as nine years for missions to the outer planets. Temperature requirements vary from tens to tenths of kelvin. At the higher temperature, cooling loads for detectors, instruments and associated shields may be as high as 15 watts. At the ultra-low temperatures, cooling loads must be limited to tens of microwatts. All systems must survive launch loads and then function in the zero gravity environment of space.

The requirements of long-lifetime, zero-g operation and a variety of temperatures and cooling loads present complex technological problems. Much progress is being made in solving these problems.

A large number of projected NASA missions will utilize instruments that require the cryogenic coolers. These include earth resources, high energy astronomy, infrared astronomy, and gravitational physics.

INTRODUCTION

The utilization and application of low and ultra-low temperature devices and systems have been increasing at a rapid pace. This is true both for NASA and DOD space flight programs as well as many research laboratories outside of NASA. Planning for future NASA missions in the next decade indicates increasing use of low and ultra-low temperature sensors and instruments.

Although some types of coolers have been flown on a few missions to date, none of the coolers can operate for the desired lifetime in zero-g and at the extremely low temperatures required in some cases. For this reason, NASA is conducting a broad-range cooler Research and Technology (R&T) program. This will assure that the required technology will be available in time to support future missions.

The objectives of this paper are to: (1) acquaint the reader with the present cooler program managed by the Office of Aeronautics and Space Technology Information Systems Office, and (2) describe changes in program thrust from that discussed in previous papers (Ref. 1 and 2). The next section will discuss the general requirements for low and ultra-low temperature and techniques that can be employed to achieve these temperatures at expected heat loads. This part of the paper will be followed with a discussion of the NASA Centers involved in the R&T efforts and the type of cooler systems on which they are focusing their effort. A brief description and thrust of R&T effort will then be given of each cooler type.

COOLING REQUIREMENTS

The expected heat loads that the coolers must be capable of handling are listed in Table I. It should be noted that the heat loads must be kept extremely small (microwatts) for operation at the ultra-low temperatures. A comparison of the data in Tables I and II allows one to determine the type of cooler most likely to be used for a particular mission category. Earth observation missions with instruments using arrays of IR sensors looking at the earth will require mechanical coolers which can supply a few watts cooling capacity and temperatures of a few tens of kelvin. Infrared astronomy missions such as IRAS (Infrared Astronomy Satellite) will use superfluid helium which can provide temperatures down to 1.5K with tens to a few hundred milliwatts cooling loads. Infrared bolometers may be required to be cooled to 0.3K using a helium-3 cooler to obtain data at longer wavelengths. For instance, the sensitivity of a bolometer continues to increase as its operating temperature is lowered. In the longer term, relativity or gravitational physics missions, which will attempt to determine the existence of gravitational waves, may require temperatures of a few millikelvin. These low temperatures can only be achieved with an adiabatic demagnetization refrigerator. In addition to mission requirements, special coolers will be required to cool experimental facilities to perform various basic science experiments in space. One of the presently approved Spacelab experiments will measure fundamental properties of superfluid helium (He II) under zero-g conditions. These are measurements on a "quantum fluid" which can only be performed under zero-g conditions. Tables I and II clearly show that different types of coolers must be available in order to meet the varying requirements (temperature, heat load/operating lifetime) placed on the cooler by different missions.

PROGRAM MANAGEMENT STRUCTURE

Because of the diversity of the cryogenic cooler program, three NASA Centers are involved in performing the Research and Technology efforts. The major areas of effort by Centers are as follows:

Goddard Space Flight Center (GSFC)

- o Long-Lifetime Mechanical Coolers
- o Solid Cryogen Coolers

Ames Research Center (ARC)

- Helium-3 Coolers
- Adiabatic Demagnetization Coolers
- Long-Life Superfluid Helium Cryostats

Jet Propulsion Laboratory (JPL)

- Radiant Coolers
- Adsorption Coolers
- Magnetic Coolers
- Spacelab Experiment - Measure Basic Properties of Superfluid Helium in Zero-g

The cooler program is managed by the NASA Headquarters Office of Aeronautics and Space Technology (OAST). Coordination is maintained with the NASA Headquarters program offices, which will be the eventual users of the new technology. This includes the Office of Space Science (OSS) and the Office of Space and Terrestrial Applications (OSTA). The cooler program activity is also reviewed in coordination meetings with DOD.

CRYOGENIC COOLER TYPES

Radiant Coolers

Radiant coolers achieve cryogenic temperatures by radiating the instrument loads to cold space. Typical operating temperatures for present radiant coolers are about 100K with a capacity on the order of 30 mW and the sensor heat dissipation but a fraction of the total. A detailed discussion of the design of radiant coolers is given in reference 3. A recent addition to the cooler R&T program is an effort by JPL to improve the performance of radiant coolers.

The JPL concept consists of a radiator plate surrounded by fixed radiation shields. Conduction heat loads to the radiator plate are reduced by the use of fiberglass tape supports with a small cross-sectional area that are capable of supporting the plate in a 1g environment, but not during launch. A caging and release mechanism is then employed for the plate. The concept could result in much larger radiant coolers in future missions with greater heat rejection capacity.

The radiant or passive cooler effort at JPL is part of an overall JPL plan to employ a combination of magnetic and gas adsorption cooler stages to pump heat from the desired low or ultra-low temperature to a sufficiently high temperature where it could be radiated to space with a radiant cooler. With no expendables, the system operating life is determined only by the reliability of the magnetic and gas adsorption cooler stages. With the JPL interest in 6 to 9 misions to the outer planets, this concept has many desirable features.

Solid Cryogen Coolers

Solid cryogen coolers utilize the heat of sublimation of cryogens to provide the cooling. To date, temperatures down to 15K, using solid neon, are considered practical. A detailed discussion of the operation of solid cryogen coolers is in reference 4.

The specific objectives of the solid cryogen cooler Research and Technology (R&T) programs being conducted by Goddard Space Flight Center (GSFC) are capacity enhancement to 3 watt-years and extension of the usable temperature range down to 8 K using solid hydrogen. To date, the emphasis has been placed upon the latter objective.

For many missions, solid cryogen coolers have the advantages of relatively simple design and elimination of zero-g fluid management considerations. Extending the cooling capacity to 3 watt-years or more will allow for a wide range of uses, including operational missions. Extending the temperature range to 8 K may allow for the cooling of infrared detectors for earth resources satellite missions by a simpler and more compact cooler as compared to a helium cooler. This could result in lower system costs.

Temperatures of 8 K to 13 K should be able to be achieved with solid hydrogen. The subliming hydrogen is exposed to the vacuum of space in order to achieve this low temperature. Solid cryogens used up to now include solid neon, which can provide temperatures of 13-24 K, solid nitrogen (43-63 K), solid agron (48-83 K), and solid methane (60-90 K).

A contractual effort is underway with Lockheed Research Laboratories to perform fill, boil-off and vent tests on a flight-type solid hydrogen cooler. Figure 1 shows a schematic of the test setup for this effort. Testing of the hydrogen cooler was successfully completed and the results will soon be documented. A smaller contractual effort with Beechcraft Corporation, in which a laboratory type cooler was filled with liquid hydrogen and then the hydrogen was frozen, is also now complete.

In order to achieve the 3 watt-year cooling capacity, heat leaks along the tank supports must be kept low by employing low conduction materials and a long conduction path. To reduce the radiant input, many layers of super insulation are utilized. The cool gas from subliming solid cryogen cools multiple metal barriers that are placed between the many layers of super insulation. It may be necessary to place a low temperature cryogen stage inside a higher-temperature cryogen system of solid ammonia or carbon dioxide, which is used to cool the outer thermal shield of the low temperature system. This is known as a two stage or guarded system.

As an example of a flight solid cryogen system, Figure 2 is a photograph of a two-stage cooler for the Limb Radiance Inversion Radiometer that was orbited aboard Nimbus-F. Figure 3 is a cut-away view of the two-stage cooler. The cooler, which was developed by Lockheed Research Laboratories, uses methane as the primary cryogen at 63 K and ammonia at 152 K as the secondary. With

6.4 kilograms of solid methane and 5.4 kilograms of solid ammonia, an operating lifetime of 7 months was achieved (ref. 4). This cooler also flew aboard the Nimbus-G spacecraft with similar performance.

Mechanical Coolers

Many of the future NASA missions require long-term cooling in the 5-10 watts load. A 3-5 year lifetime mechanical cooler offers a compact, low-weight system for accomplishing this goal. It is virtually the only practical system for covering this requirement. Prime mission types include long-duration gamma-ray astronomy, atmospheric research, earth resources and weather satellites. Many types of Shuttle Sortie missions (1 to 4 weeks duration) would also benefit from a reliable mechanical cooler.

Goddard Space Flight Center is the lead Center in the efforts to develop reliable mechanical coolers. The specific objective is to develop the technology for a 3-5 year lifetime cooler that will provide 5 watts of refrigeration at 65 K. After achieving this objective, efforts will be concentrated on extending this technology to the 12 K region.

The basic problem is to develop a closed cycle machine with moving parts that will run reliably for billions of cycles while unattended. Past attempts to solve this problem have used liquid or semi-liquid lubricants, dry lubricants, and "hard-on-hard" bearings with little or no lubricant. Various seal designs were also tried. To date, these approaches have not yielded a long-lifetime spaceborne cooler system.

The new approach initiated by NASA Goddard Space Flight Center hopefully eliminates the problem-causing features of the past. The key elements of the approach are: (1) the reciprocating components are driven directly with linear motors, and (2) while operating, there is no contact between the moving components and the machine housing or motor. The noncontact operation can be achieved by either magnetic or gas bearings and clearance seals. Consequently, two major contractual efforts have been funded - one to develop the magnetic bearing cooler and the other to develop the gas bearing machine.

To date, the Phase 1 design and component test activities for both the gas and magnetic bearing coolers are complete. Fabrication of the magnetic bearing design has begun, with a scheduled delivery of an engineering model cooler in January 1981. From this point on, most of the effort will be concentrated on the magnetic bearing cooler, although some component level development of gas bearings will continue.

A schematic of the Philips Laboratory magnetic bearing cooler is shown in Figure 4. The piston and the displacer are sinusoidally oscillated by the linear motors shown. These reciprocating elements are accurately positioned in their respective cylinders using active magnetic bearings. These bearings employ eddy current sensors to monitor the gap at two positions, 90° apart, around the cylinder circumference. The signals are used to adjust the currents in the four circumferential electro-magnets. The centering accuracy of these

bearings is better than 0.025 mm (0.1 mil) and they permit the efficient use of piston and displacer clearance seals which are an order of magnitude larger. Magnetic bearings support the piston on each side of the piston motor. In this manner, they equally share any radial instability force developed by the motor. A moving magnet motor design, as opposed to a moving coil, provides high reliability without flexing leads. The motor coils are hermetically sealed in metal cans to eliminate outgassing products which can affect long-term cooler stability.

The room temperature portion of the displacer is guided by two magnetic bearings. These bearings are located at the 300 K ambient temperature heat exchanger as shown. In the engineering model cooler, the displacer is driven in both directions and a restoring spring is not employed. A penalty in drive power will be paid for the simplicity of this design. A restoring "magnetic spring" may be included in future models.

The piston and displacer amplitudes and relative phase are under closed loop control. The peak-to-peak amplitude of the piston is monitored using two LVTD's. Phase control is required to maximize cooling capacity and thermal stability. The power requirement for the 5 watt, 65 K Philips cooler is about 170 W and the machine is about 70 cm long.

The quest for a reliable spaceborne mechanical cooler has been an extremely difficult one. It is hoped that the innovative approach of the Goddard Space Flight Center will result in a major breakthrough.

Adsorption Cooler

A concept for an adsorption refrigerator that is being developed by the Jet Propulsion Laboratory (JPL) is shown in Figure 5. Heat is used to compress the working gas by driving it from a zeolite adsorber. The gas is then driven through an expansion engine or a Joule Thomson device to provide the cooling. The downstream section of the cooler is maintained at near vacuum conditions by maintaining the adsorber at a low temperature through the passive radiator. When all of the working fluid ends up in the downstream adsorber, the cycle must be reversed. This is accomplished by appropriately reversing the positions (i.e., open to closed and vice versa) of the downstream and upstream heat switches and valves.

The adsorption refrigerator has the advantage of relatively few moving parts. Questionable areas are its efficiency and need for a radiant cooler. Work is progressing on the development and engineering model cooler at JPL.

Magnetic Coolers

The concept of a continuously operating magnetic cooler is also being pursued by JPL. W. A. Steyart of Los Alamos Scientific Laboratory (LASL) has published results of his work (ref. 5) on the magnetic cooler. LASL is presently cooperating with JPL to further define the concept.

The magnetic cooler can operate with efficiencies of 80% of Carnot, or greater, in the temperature range of 2 to 20 K. No high pressure seals are required. Low speed operation with a minimum number of moving parts appears possible. However, a large magnetic field of 5 to 7 Tesla is required for efficient operation.

Figure 6 shows one proposed system concept. The magnetic cooler pumps heat from the sensor load at 2.2 K to a temperature of 17 K. Additional magnetic or adsorption cooler stages would then pump the heat to a temperature of 180 K where it would be radiated to space by a large, but lightweight, radiator.

The operation of the rotating magnetic cooler is as follows: The rim of the wheel is made of porous $Gd_2\ (SO_4)_3$, $8H_2O$, $Gd_2\ (SO_4)_3$, or Gd PO_4 The application of the magnetic field to the wheel in the small region shown will produce adiabatic heating. The heat is removed by the high temperature loop. As the Gd moves out of the magnetic field it drops in temperature (as much as 14 K) due to adiabatic cooling.

The rotating magnetic cooler considered by Steyart (ref. 5) allowed cycle times of much less than 1 second, that is, a wheel rotation rate of 1 to 5 revolutions per second. Circulating fluids forced through the porous wheel exchange the heat.

Stored Liquid Helium Coolers

Liquid helium (He^4) at atmospheric pressure is at a temperature of 4.2K. By pumping on the liquid helium the temperature can be lowered to 1.2 to 1.5K. At these temperatures, all other normal substances, except helium-3, are solids. Because of the low latent heat of liquid helium, high quality dewars of cryostats must be used to prevent rapid loss of the liquid.

The common isotope of helium (He^4) above 2.17K (the lambda point) is a normal liquid in all respects. Special effort must be taken to maintain thermal contact between the cryogen and the heat load. Approaches include surface tension, position retention, thermally conductive nets, and continuous acceleration by rotation of the dewar. At temperatures below 2.17K, normal helium (He I) becomes a superfluid (He II) with a thermal conductivity almost 1000 times that of copper at room temperature and almost zero viscosity. It forms a thin film on exposed surfaces. Furthermore, it moves to the warmer region which is what one would want a liquid to do if one desired an extremely uniform temperature throughout a large volume.

At present, it appears that superfluid helium has many desirable properties which make it the prime choice for cryogenic cooling in the 1.5 to 10K temperature range in systems with heat loads in the range of ten to a few hundred milliwatts. Reasonably sized cryostats can provide continuous cooling for infrared astronomy missions for periods of one year in space with expected heat loads from detectors and preamplifiers (ref. 6). With improved techniques for

installing multilayers of insulation and new designs for the inner tank supports, operating lifetimes with expected heat loads of up to three years appear possible. Consideration is being given to new designs for fiberglass tank supports. Retractable supports are also being considered. However, practical methods are needed to "fill" the hole in the super insulation blanket when the tank supports are retracted. Guarded systems using low-temperature solid-cryogen (e.g., hydrogen) or a mechanical cooler to cool the outer metal shield are another approach to achiving a 3 to 5 year life cooler.

Helium-3 Coolers

The availability of quantities of the pure isotope helium-3 (He^3) in the late 1950 time period led to its widespread use as a means of achieving lower temperatures. This is because the vapor pressure of this isotope is much higher at a given temperature than that of helium-4 (He^4). For example, at 1K, liquid He^3 (normal boiling point 3.2K) has a saturated vapor pressure 80 times larger than He^4. By appropriately pumping on He^3, temperatures of about 0.3K can be attained.

Ames Research Center is pursuing R&T efforts on He^3 coolers that can operate in zero-g. Because of the high cost of He^3, it must be used in a closed-cycle mode. Special techniques must be employed to control the location of the liquid and to maintain thermal contact with the sensor or parts to be cooled.

Figure 7 is a photograph of an ARC prototype He^3 cooler. The He^3 is absorbed in a zeolite bed as it evaporates from the copper foam. To recycle, the zeolite is heated to pressurize the He^3 vapor and the copper foam is cooled to liquid helium (He^4) temperatures (probably superfluid helium at less than 2K temperature). The He^3 is then condensed onto/into the copper foam. If continuous or semi-continuous cooling is desired, multiple units might be employed with one unit being recycled while the other unit is providing temperatures as low as 0.3K.

Initial tests have shown that the unit will operate in either an upright or inverted (negative g) position. Other tests will be performed on the NASA Lear Jet and KC-135 airplanes which can provide about 30 seconds of nearly zero-g environment.

The lower temperature provided by the He^3 cooler (0.3K) as compared to a superfluid He^4 cooler (1.5K) can provide greatly increased performance for bolometer infrared detectors. In fact, the sensitivity of a bolometer IR detector will increase by a factor of 50 if cooled to 0.3K instead of 1.5K.

Joule-Thomson Cooler

Another type of cooler in which Ames Research Center (ARC) and the Jet Propulsion Laboratory (JPL) have performed preliminary tests is the Joule-Thomson expander (JTX). For this cooler, the helium may be stored under super-

critical conditions. This eliminates consideration of liquid/gas location and maintaining thermal contact in zero-g. Temperatures down to 1.4K have been achieved.

The concept has the advantage of a simplified helium storage system at pressures between 0.35 and 2.07 MPa (50 and 300 psi). Tests run on the JTX have shown sufficiently low noise levels generated by the expansion process that it will not affect the performance of infrared detectors.

Tests to date have shown that supercritical helium storage with a JTX is a viable alternative to the superfluid helium cooler for obtaining temperatures at least down to 2K with heat leaks in the tens to few hundred milliwatts range. It is being considered as one of the candidate coolers for the Shuttle Infrared Telescope Facility (SIRTF). The concept also has the advantage that there is no liquid sloshing to affect telescope pointing stability.

Adiabatic Demagnetization Cooler

The lowest practical temperature that can be produced by pumping on He^3 liquid is around 0.3K, and, on He^4 liquid is in the range of 1.2K to 1.5K. A technique by which temperatures approaching a few microkelvin has been achieved in the laboratory depends on the magneto-thermodynamic properties of complex salts. The principle of operation is as follows: the paramagnetic salt is suspended in liquid helium. A magnetic field is applied. The salt will derive energy from the magnetic field which appears as heat and raises the temperature of the salt. However, the salt is soon cooled down to the liquid helium temperature. The salt is then removed from the liquid helium and then the magnetic field is removed. The salt now cools practically instantaneously to a very low temperature.

The salt will warm up as it provides the desired cooling function. The rate at which it warms up depends on the amount of salt, the cooling load, and the degree of isolation provided by the cryostat design. After a period of time, the magnetization, cooling, and demagnetization cycle must be repeated. Multiple units might be employed whereby one is being recycled while other units are acting as coolers.

NASA Ames Research Center is performing preliminary studies on this cooling concept for space missions. Ground-based systems have been used for a number of years. The objective of the NASA program is to provide the technology to achieve a reliable space qualified cooler.

Millikelvin temperatures may be necessary for operating Weber bar-type gravitational wave detectors in space. This low temperature may provide the required sensitivity (high Q for the single crystal silicon or sapphire rod) and stability.

It is expected that the R&T program can provide the technology required to design a flight type adiabatic demagnetization cooler to achieve temperatures of a few millikelvin. The particular cooler system chosen for a given mission

will depend on the simplicity and reliability that future R&T efforts can provide for each of these systems. In all cases, cooling loads (including heat leaks) must be limited to tens of microwatts.

PRESENT/FUTURE APPLICATIONS

Table III provides a selected listing of potential future NASA missions which will use cryogenic coolers. The status of the project, the temperature required, and the potential launch date are identified for each mission identified. It should be clear to the reader that cryogenic coolers for low and ultra-low temperatures will eventually be in use on many NASA spacecraft. R&T efforts to either obtain or improve the required technology for the system design obviously have high priority. Greatly improved data with increased accuracy and resolution could be obtained with new sensors. However, these sensors must be cooled to the temperatures as indicated on Table III.

CONCLUSION

An overview of the NASA/OAST Low and Ultra-Low Temperature Cooler Research and Technology Program has been presented. Its purpose has been to acquaint the reader with the future requirements for coolers, the present status of technology, and the activities in progress to provide new technology to meet the requirements of coolers for future missions.

The areas of emphasis in a Research and Technology effort will naturally change as requirements evolve and as results from the investigations become available. Thus, this paper should be considered a status report of present activities.

REFERENCES

1. Lundholm, J. G.: NASA Low and Ultra-Low Temperature Cryogenic Cooler Systems for Space Missions. ISA Transactions, Vol. 19, No. 1, pp. 3-14.

2. Sherman, A.: Cryogenic Cooling for Spacecraft Sensors, Instruments, and Experiments. Aeronautics and Astronautics, Vol. 16, No. 11, November 1978, pp. 39-47.

3. Donohoe, M.; and Sherman, A.: Radiant Coolers-Theory, Flight Histories, Design Comparisons and Future Applications. AIAA Paper No. 75-184, Presented at 13th Aerospace Sciences Meeting, Pasadena, CA, January 1975.

4. Nast, T. C.; Barnes, C. B.; and Wedel, R. K.: Development and Orbital Operation of a Two-Stage Solid Cryogen Cooler. Journal of Spacecraft and Rockets, Vol. 15, No. 2, pp. 85-91, Mar-Apr 1978.

5. Steyart, W. A.: Rotating Carnot Cycle Magnetic Refrigerator for Use Near 2K. Journal Applied Physics, Vol. 49, No. 3, March 1978, pp. 1227-1231.

6. Urbach, A. R.; Vorreiter, J.; and Mason, P.: Design of a Superfluid Helium Dewar for the IRAS Telescope. Presented at 7th International Cryogenic Engineering Conference, July 4-7, 1978.

TABLE I.- GENERAL NASA MISSION CATEGORIES REQUIRING LOW AND ULTRA-LOW TEMPERATURE COOLERS

DISCIPLINE	APPROXIMATE TEMPERATURE RANGE (KELVIN)	APPROXIMATE RANGE OF REFRIGERATION LOAD
APPLICATIONS MISSIONS (WEATHER, EARTH RESOURCES, POLLUTION MONITORING, ETC.)	10-100	MILLIWATTS TO 10 WATTS
HIGH ENERGY AND GAMMA-RAY, ASTRONOMY	4-100	MILLIWATTS TO 10 WATTS
INFRARED ASTRONOMY	0.3-10	MICROWATTS TO 100 MILLIWATTS
RELATIVITY MISSIONS	0.001-1.5	MICROWATTS TO MILLI-WATTS
SUPERCONDUCTING DEVICES	1-15	WIDE RANGE
BASIC RESEARCH EXPERIMENTS	1-10	$<$100 MILLIWATTS

TABLE II.- LOW AND ULTRA-LOW TEMPERATURE SPACE COOLING TECHNIQUES

COOLING TECHNIQUE	APPROXIMATE PRACTICAL* TEMPERATURE RANGE (°K)	APPROXIMATE RANGE OF* USABLE REFRIGERATION LOAD FOR 1 YEAR MISSION
RADIANT COOLERS	70-100	0-100 MILLIWATTS
STORED SOLID CRYOGEN COOLERS	10-90	0-800 MILLIWATTS
MECHANICAL COOLERS	4-100	0-100 WATTS
ADSORPTION COOLERS	0.2-100	0-10 WATTS
MAGNETIC COOLERS	0.2-100	0-10 WATTS
STORED LIQUID HELIUM COOLERS	1.5-5.2	0-100 MILLIWATTS
He^3 COOLERS	0.3	0-100 MICROWATTS
ADIABATIC DEMAGNETIZATION COOLER	0.001-0.3	0-100 MICROWATTS

*THESE VALUES ARE THE GOALS OF THE DESIGN CONCEPTS

TABLE III.- POTENTIAL FUTURE MISSIONS REQUIRING LOW TEMPERATURE COOLERS

	Mission	Status	Temperature Required (°K)	Potential Launch Date
A.	**Infrared Astronomy Missions**			
	1) Infrared Astronomy Satellite	Approved Project	3	1981
	2) Shuttle Infrared Telescope Facility	Study & R&D	1.8	1986
	3) Small Infrared Telescope	Approved-Spacelab	3	1982
	4) Cosmic Background Explorer	Study	1.8	1984
	5) Outer Planets Radiometry	Concept	1.8	Late 1980's
B.	**Atmospheric Physics**			
	1) Cryogenic Limb Scanning Interferometer Radiometer (CLIR)	Study	10	1985
	2) Upper Atmosphere Research Satellite	Study	10 (Several Instruments)	1985
	3) Laser Heterodyne Spectrometer	Study-Spacelab	15 to 45	1986
C.	**Relativity Missions**			
	1) Gyroscope Test of General Relativity	Pre-Project R&D	1.5	Late 1980's
	2) Gravitational Wave Detection	Concept	0.001 to 0.1	
D.	**Particle/Gamma Ray Astronomy Missions**			
	1) Gamma Ray Observatory	Study	80	1984
	2) Broadband X-ray Experiment	Approved	80	1985
	3) Cosmic Ray Experiment	Study-shuttle	4	1986

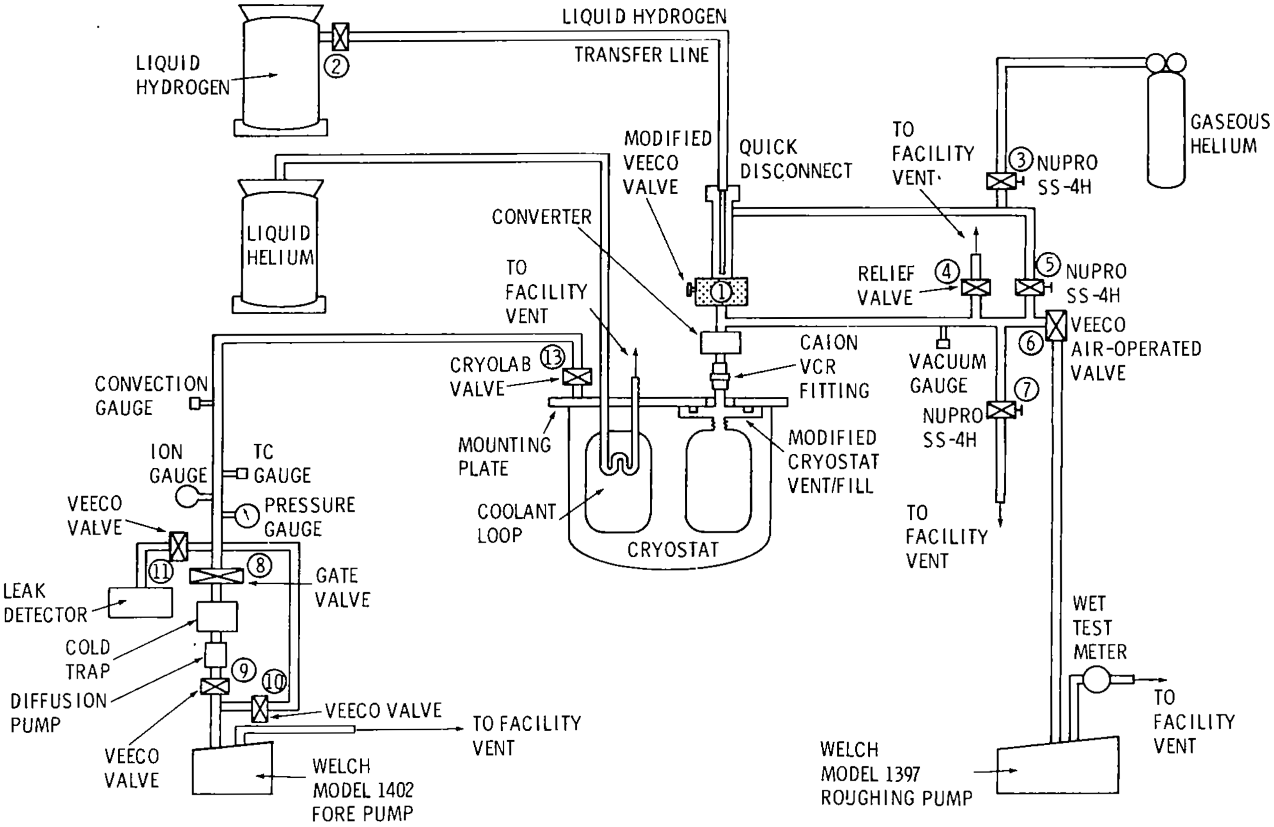

Figure 1.- Solid hydrogen test schematic.

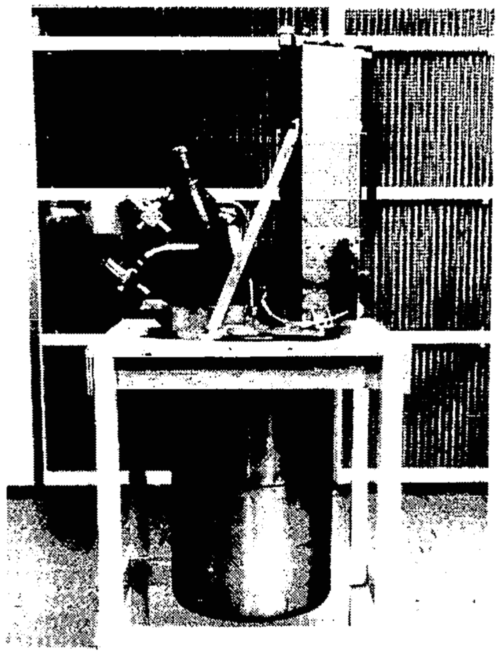

Figure 2.- Solid cryogen cooler (built by Lockheed Palo Alto) for Limb Radiance Inversion Radiometer (LRIR).

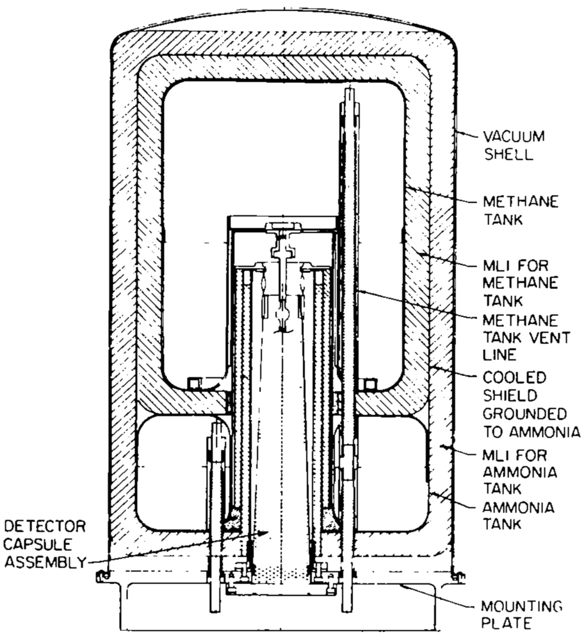

Figure 3.- Cut-away view of solid cryogen cooler (built by Lockheed Palo Alto).

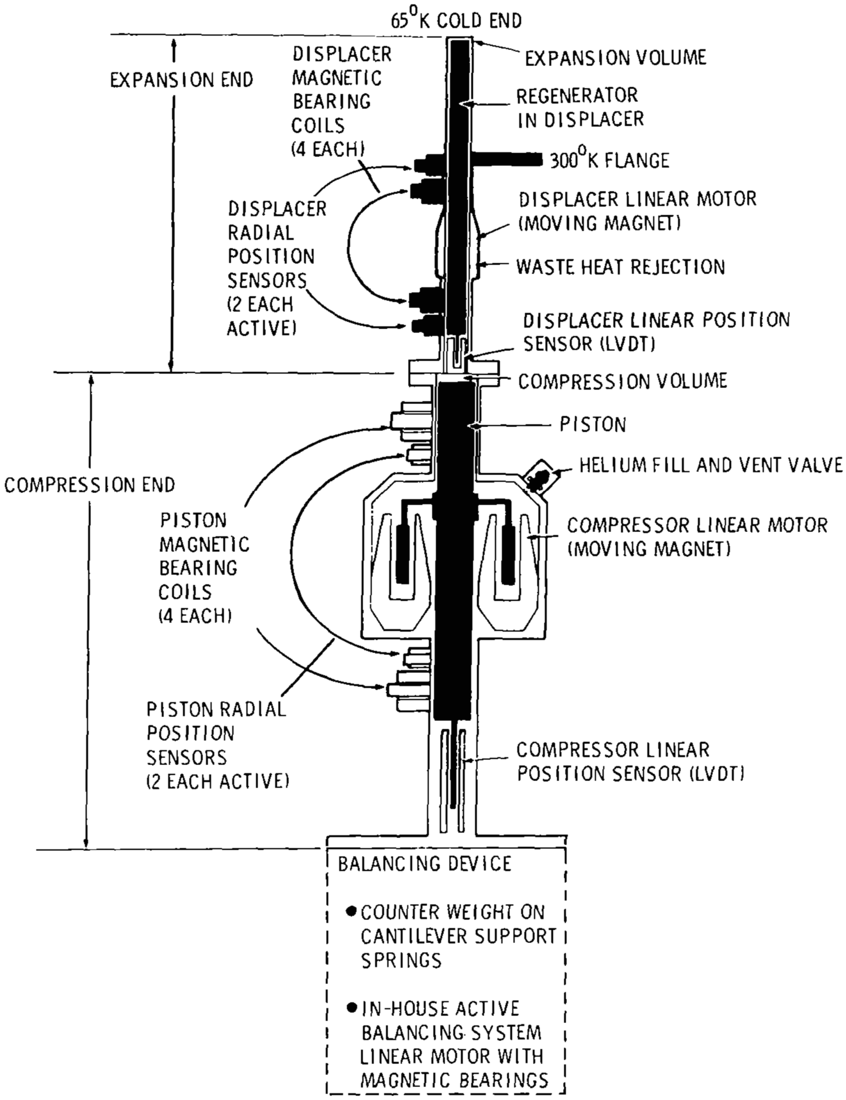

Figure 4.- Single expansion cryogenic cooler with linear magnetic suspension.

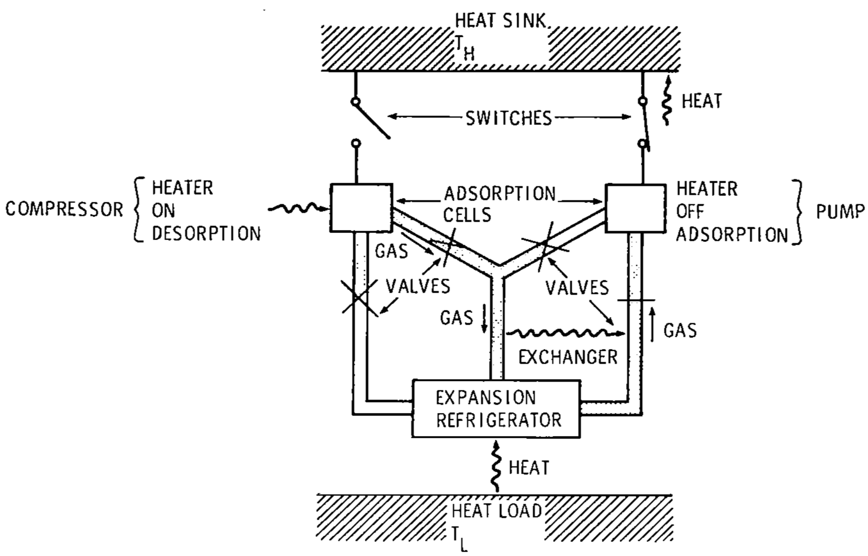

Figure 5.- Adsorption pump-compressor for expansion refrigerator.

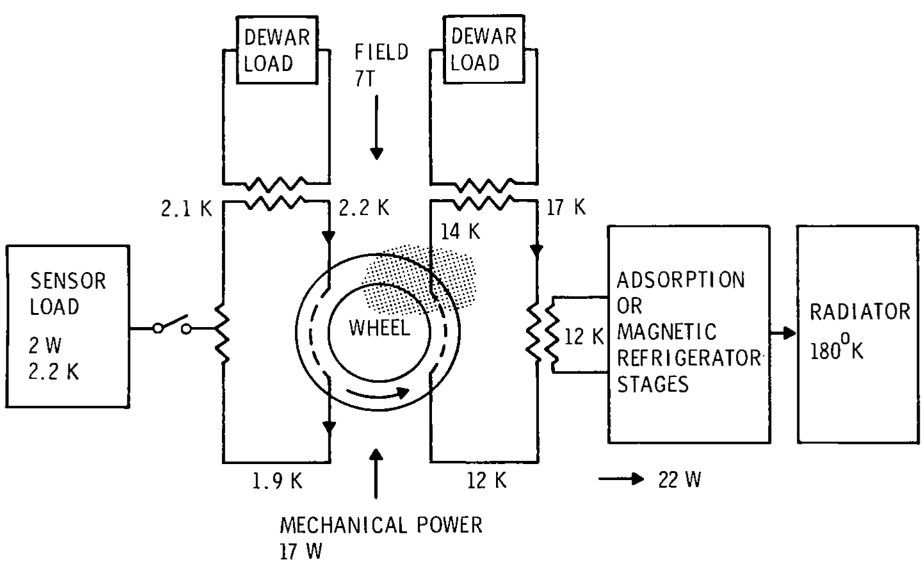

Figure 6.- Concept for spacecraft low temperature magnetic refrigerator.

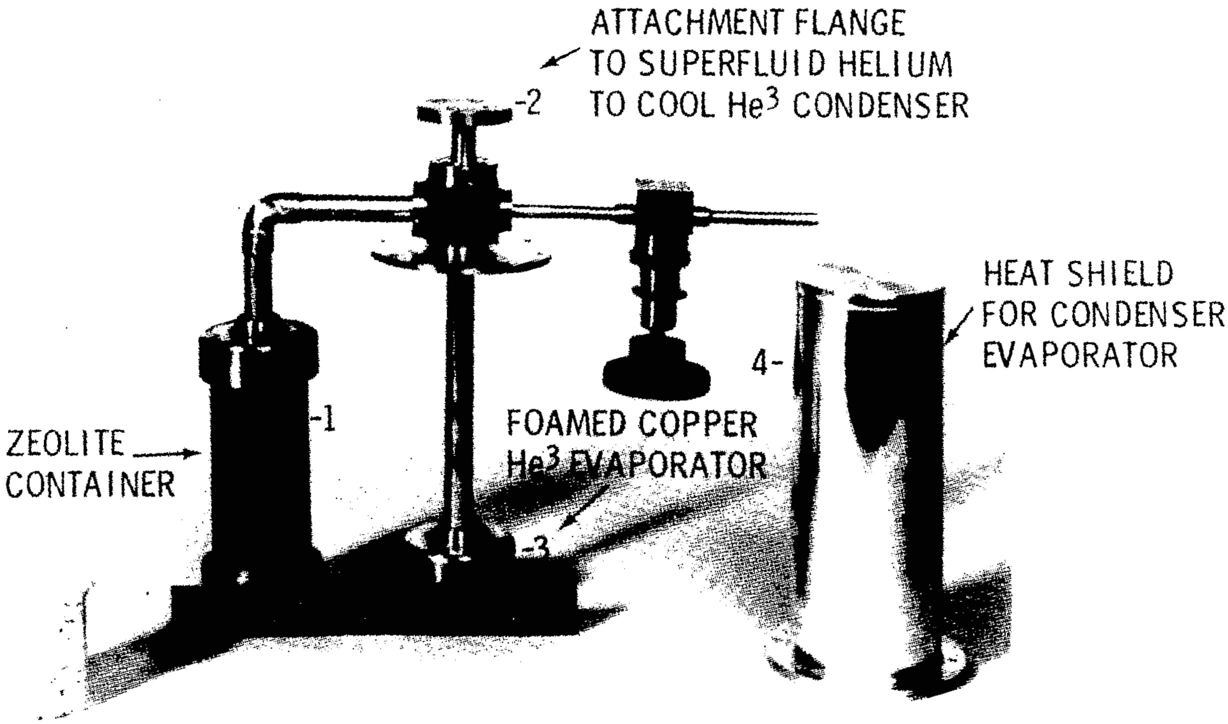

Figure 7.- He^3 cooler prototype designed by Ames Research Center.